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European wind variability over 140 yr

P. E. Bett, H. E. Thornton, and R. T. Clark

Met Office Hadley Centre, Exeter, UK

Abstract. We present initial results of a study on the variability of wind speeds across Europe over the past 140 yr, making use of the recent *Twentieth Century Reanalysis* data set, which includes uncertainty estimates from an ensemble method of reanalysis. Maps of the means and standard deviations of daily wind speeds, and the Weibull-distribution parameters, show the expected features, such as the strong, highly-variable wind in the north-east Atlantic. We do not find any clear, strong long-term trends in wind speeds across Europe, and the variability between decades is large. We examine how different years and decades are related in the long-term context, by looking at the ranking of annual mean wind speeds. Picking a region covering eastern England as an example, our analyses show that the wind speeds there over the past ~ 20 yr are within the range expected from natural variability, but do not span the full range of variability of the 140-yr data set. The calendar-year 2010 is however found to have the lowest mean wind speed on record for this region.

1 Introduction

Knowing the form of the wind speed distribution is of critical importance when assessing the wind energy potential at a site. Typically, when wind farm developers or investors consider a site, they assess it using (at best) the past 20–30 yr, with data from direct observations, NWP models, and reanalyses. These recent decades reflect our personal experience of wind speeds, but they do not show the longer-term historical context. Understanding whether the most recent decades were more or less windy than normal, or if there are any significant long-term trends, is key to understanding the range of possible future windspeeds we might experience over the coming ~ 5 yr, or over the lifetime of a wind farm (~ 25 yr). This information is important not just for managing wind farms, but also for planning investment in future wind energy projects.

In this study, we show wind speed distributions for Europe over 140 yr (1871–2010), utilising the *Twentieth Century Reanalysis* data set (20CR, Compo et al., 2011). This reanalysis incorporates observations of sea-level pressure and surface pressure alone, with sea-surface temperature and sea-ice concentration data used as boundary conditions. The reanalysis used an experimental coupled atmosphere–land version of the NOAA NCEP Global Forecast Model, ran with 56 ensemble members. This allows an estimate of the uncertainties present due to episodes with less data (for example due to the reduction in Atlantic shipping during the World Wars, or the overall reduction in observations as one looks further back in time). We use the daily-mean wind speeds at the near-surface pressure level where $P/P_{\text{surface}} = 0.995$, on a regular lat–lon grid of resolution $2^\circ \times 2^\circ$. Other studies of European wind speed climatologies have used data sets that assimilate more observations or are at higher resolution. For example, the studies of Kiss and Jánosi (2008), Pryor et al. (2006), and Siegismund and Schrum (2001) use the ERA-40 (Uppala et al., 2005) and NCEP/NCAR reanalyses (Kalnay et al., 1996), which both span ~ 50 yr. The key feature of the use of the 20CR in our study is the unprecedented length of the time series, which allows us to compare decadal-scale fluctuations in the speed and variability of the wind.

In this short article, we present an initial sample of our results. We reserve a more full analysis for a later publication.

2 Results

2.1 Wind speed and variability

The simplest way of describing the long-term wind speed distribution over Europe is to map the long-term mean and standard deviation of the daily wind speeds. The long-term average is simply the mean of the daily wind speeds from all days from all ensemble members. For the standard deviation, we need to take account of the structure of the 20CR ensemble: the 56 members of the reanalysis were run as a series of independent "streams", each covering consecutive 5-yr periods[1] (see Table III in Compo et al., 2011). The result of

Correspondence to: Philip Bett
(philip.bett@metoffice.gov.uk)

[1]Streams 16 and 17 actually have lengths of 6 and 4 yr respectively, and stream 27 consists of 10 yr (1999–2010). We treat the

this is that a time series from an ensemble member is only temporally continuous for 5 yr, and aggregating over any period longer than this risks mixing interannual variability with ensemble member-to-member variability. Therefore, for the long-term standard deviation, we first calculate standard deviations in 5-yr periods for each ensemble member. We then take ensemble means, giving us a single standard-deviation time series in 5-yr steps. These are then aggregated into a single long-term ensemble-mean value, using[2]

$$\sigma^2 = \frac{\sum_i N_i\left(\sigma_i^2 + \bar{U}_i^2\right)}{\sum_i N_i} - \bar{U}^2, \tag{1}$$

where N_i is the number of days in the 5-yr period i, the ensemble-means of the 5-yr mean and standard deviations of the daily wind speeds are $\bar{U}_i$ and σ_i respectively, and the long-term mean wind speed is $\bar{U} \equiv \left(\sum_i \bar{U}_i\right)/28$.

We show the resulting long-term maps in Fig. 1. The areas with the highest wind speeds, and the greatest day-to-day variability, are over the sea rather than the land. In particular, the highest-wind regions are in the north Atlantic, west of Ireland and north of Scotland. Relatively high winds also cover the rest of the British Isles and the coastal areas of north-western Europe, as well as the central Mediterranean.

The extremely low winds over the areas of more complex orography (in an arc from the Atlas Mountains, over Spain, the Alps, the Carpathians, and through to Turkey) are likely to be due to the drag scheme used to model the impact of unresolved orography. (Note that the horizontal scale of the mountains is much smaller than the grid size used here.) While such features are often seen in maps of model wind speeds (e.g. Howard and Clark, 2007), it is important to be particularly wary of the results in these areas, as it is not clear how to relate them to the real physical situation 'on the ground'.

We have tested for the presence of any long-term trends, by performing a simple linear regression on the ensemble-mean time series of 5-yr means and standard deviations of the wind speeds in each grid cell. The significance of any trend (i.e. whether the gradient of the linear fit was significantly different from zero) was assessed using a t test at the 0.1% level. Figure 2 shows the long-term trends, shaded out when they are not statistically significant.

While most areas over Europe show no significant trend, there are some areas of interest: the Atlantic off the north and west coasts of Ireland and Scotland shows a significant positive trend (with the mean wind speed increasing at a rate of $\sim 0.03\,\mathrm{ms^{-1}decade^{-1}}$), as does the eastern Mediterranean around Crete and Turkey ($\sim 0.07\,\mathrm{ms^{-1}decade^{-1}}$). There is a significant negative trend in the central Mediterranean around Sicily and Malta ($\sim -0.05\,\mathrm{ms^{-1}decade^{-1}}$). Note, however, that even where the trends are significant, they are still extremely small: a change of $\sim \pm 1\,\mathrm{ms^{-1}}$ per two centuries. The standard deviation trend map shows similar spatial patterns, but even fewer and smaller areas where those trends are significant.

We show an example time series in detail in Fig. 3, to illustrate some general features of the wind time series over Europe, and to show the benefits of being able to use such a long data set. It uses daily wind speeds averaged over a region covering eastern England (see box in Fig. 1). This region has been selected partly because it is an area of interest for future wind farm development[3], but also because

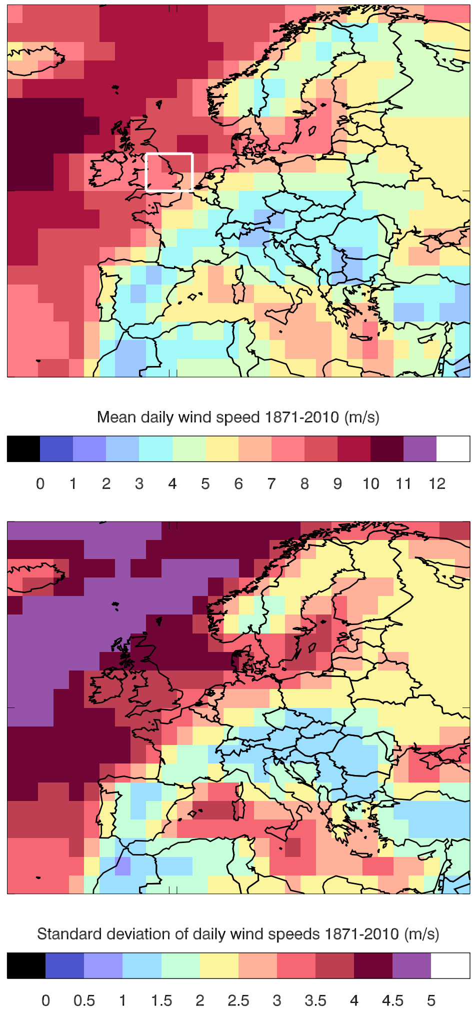

Figure 1. Maps of the 140-yr mean and standard deviation of the daily wind speeds from 20CR. The white box in the top plot marks the region we refer to as 'eastern England'.

whole series as 28 equal periods of 5-yr, for simplicity.

[2]Note that equation (1) is for the population standard deviation, which we use as we are aggregating data covering the complete time period, rather than estimating σ from a sample of years.

[3]See e.g. maps on the UK Government's RESTATS web site http://restats.decc.gov.uk/app/pub/map/map/ and the UK Crown Estate's web site

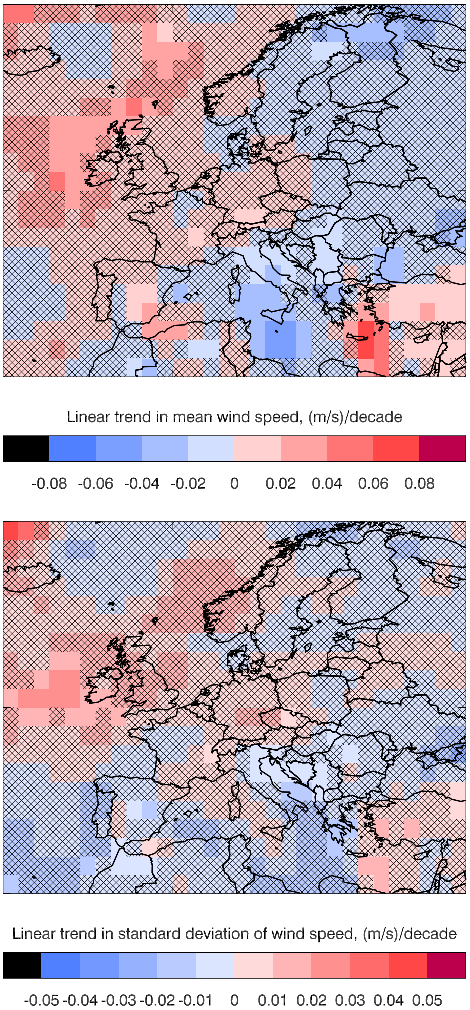

Figure 2. Gradients of the linear regressions to the 140-yr time series of 5-yearly ensemble-mean average wind speeds (top) and standard deviations of daily wind speeds (bottom). Shaded areas show where the trend is not statistically significant at the 0.1% level.

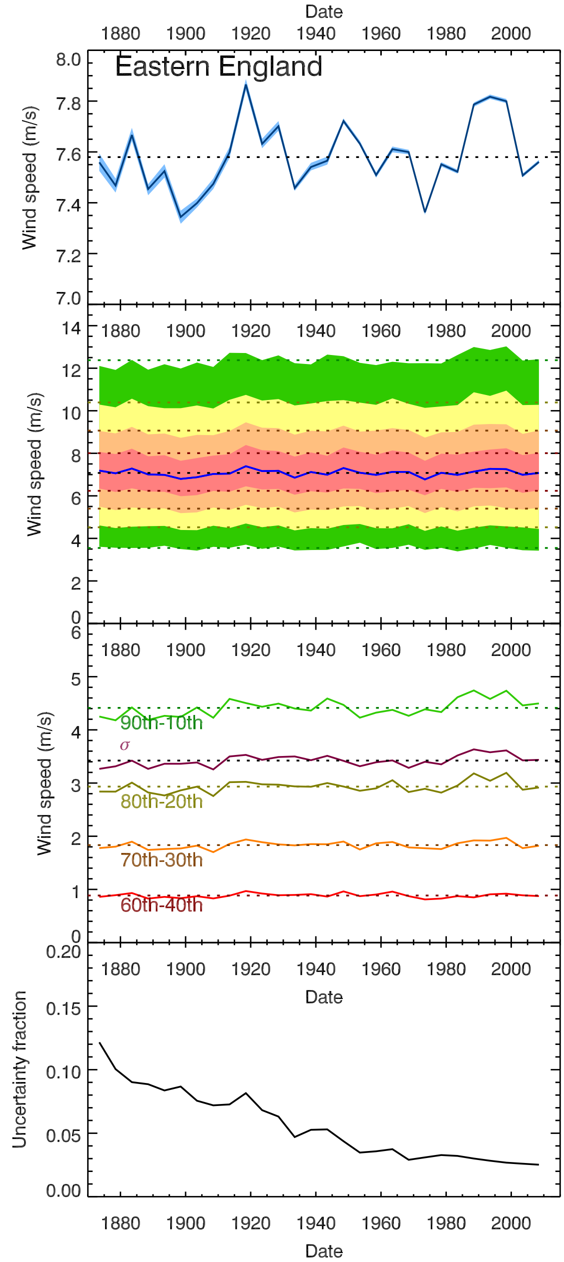

Figure 3. Time series of the wind speed distribution averaged over the eastern England region. Top: Ensemble mean of the 5-yr mean wind speed, with lighter shading indicating the 10th and 90th percentiles of the ensemble member distribution (most visible at early times). Second from top: the ensemble mean of the 5-yr median wind speed (blue line), as well as the other deciles (coloured regions, from 10th percentile at the bottom to the 90th percentile at the top). The long-term means of the deciles are shown by dotted lines. Widths of the distribution are shown in the panel second from bottom: Half the difference between ensemble-mean deciles (as labelled), and the ensemble mean of the standard deviation of ensemble members' wind speeds in 5-yr bins (labelled σ). Bottom: 5-yr means of the day-to-day ensemble spread (i.e. standard deviation of the ensemble members each day), as a fraction of the ensemble-mean 5-yr mean wind speed.

it avoids some of the more exceptional features already discussed, such as the artificially low winds seen over complex terrain and the weak trends seen further to the north-west. We reserve a more detailed discussion of such features for subsequent papers.

The 5-yearly mean wind speeds (top panel of Fig. 3; note the magnified scale) clearly show the peak in the late-1980s up to around 2000, and the subsequent return to the long-term mean. We can also see that this excursion from the mean, while strong, is not exceptional in the long-term history of this region (see e.g. the peak in the 1915–1920 period, and the prolonged reduction over 1885–1910). There is also no clear trend.

http://www.thecrownestate.co.uk/energy-infrastructure/downloads/maps-and-gis-data/

By looking at the deciles of the distribution (second panel in Fig. 3), we can see how different features appear at different levels. For example, there is a clear trough in the early 1970s in the central region of the distribution; it doesn't appear in the 10th and 90th percentiles, and only forms part of a much broader reduction in the 80th percentile. The length and form of the reduction around the 1890–1910 period is also different in different deciles, with the upper deciles showing a longer reduction in wind speed. These features can be tracked through into the distribution widths (third panel of Fig. 3): for example, the dip in the widths over 1905–1910 is due to the lower deciles rising while the upper deciles are still low. The actual meteorological situations in these periods would need to be investigated in more detail to understand the underlying physical causes, but these features show the importance of analysing the whole distribution beyond just the mean.

The day-to-day ensemble spread as a fraction of the mean wind speed is shown in the bottom panel of Fig. 3. This will always be much greater than the uncertainty in the 5-yr mean shown in the top panel; nonetheless, it illustrates a general decrease in the uncertainty in the data, with an average daily spread between the ensemble members of about 2.5% of the mean wind speed by the 2000s. This reduction in uncertainty is directly related to the dramatic increase in the amount of data assimilated over the course of the 20CR period, which constrains the ensemble members reducing their spread (see discussions in e.g. Compo et al. 2011; Ferguson and Villarini 2012; Krueger et al. 2012; Wang et al. 2012). It is important to note that this panel shows the *uncertainty* in the reanalysis (through the daily ensemble spread), whereas the σ in the panel above refers to the *variability* of wind speeds over time in all ensemble members.

2.2 The Weibull distribution

Distributions of wind speeds at given locations are commonly modelled as being drawn from a Weibull distribution (e.g. Conradsen et al., 1984; Carta et al., 2009, and references therein), which has the probability density function (PDF)

$$P(U) = \frac{k}{\lambda}\left(\frac{U}{\lambda}\right)^{k-1} \exp\left[-\left(\frac{U}{\lambda}\right)^{k}\right], \qquad (2)$$

where the random variable U is the wind speed, k is the (dimensionless) shape parameter, and λ is the scale parameter (in the same units as U). The form of the distribution for different values of k and λ is shown in Fig. 4. The shape parameter k determines the overall form of the distribution, including the skewness, and the width for a given λ; for wind speeds, k tends to lie between 2 and 3. For a given shape, the scale parameter λ determines the distribution's peak-location and width; higher values of λ result in a broader distribution with a peak at a higher wind speed. We can use the Weibull parameters as an alternative way of characterising the wind speed distribution. Examining changes in the Weibull parameters allows us to track the behaviour of the distribution as a whole, rather than e.g. just the mean value.

In a given grid cell or region, we find maximum-likelihood estimates of the Weibull scale and shape for the distribution of daily wind speeds of each ensemble member in each 5-yr period. This yields ensemble estimates of the time series of Weibull parameters; an example from the same eastern England region as before is shown in Fig. 5. As expected, the behaviour of the scale parameter over time is similar to the mean and σ time series (Fig. 3), whereas this is not seen in the shape parameter. As the shape parameter governs the skewness of the distribution, the variation in k could be related to the presence of extreme high-wind events, as these could cause the form of the distribution to be fit better with a longer tail.

Once again, we can extract linear trends from these time series, test their significance, and map the results along with their long-term values. The long-term mean and trend of the shape parameter are shown in Fig. 6. The map for the average k shows very little spatial variability, staying in most areas between 2 and 3. Very few areas show any significant trend, although there is again an area of reduction over the central Mediterranean (i.e. tending to a more skewed distribution) and growth around Crete (towards a more symmetric distribution). The long-term mean and trend of the scale parameter is shown in Fig. 7. The mean-λ map is very similar to both the mean and standard deviation of the wind speeds (cf. Fig. 1), and the trend map is again familiar; the area of significant growth in the north-east Atlantic is in this case much larger.

The distribution width is related to *both* λ and k, but in opposite senses (e.g. narrower distributions can be obtained by reducing λ or increasing k, with corresponding impacts on the peak locations and skewness). Thus, it is not surprising that (for example) the negative trends in both k and λ over Italy and the Tyrrhenian Sea do not correspond with a significant trend in the wind speed standard deviation (cf. Fig. 2).

It is important to note again that, regardless of statistical significance, the trends present in both k and λ are still exceedingly small.

2.3 Year-ranking by wind speed

An additional way of relating the wind speeds in different years to the long-term context is to plot the annual mean wind speeds in rank order. This is shown qualitatively in Fig. 8, for the eastern England region. We can immediately see that the day-to-day variability in wind speed is much larger than the year-to-year variability (in annual-mean wind speed), and the mixture of colours shows the lack of a clear long-term trend.

We can get a more quantitative picture by highlighting individual decades. Fig. 9 shows how the most recent three decades are positioned with respect to the 140-yr time series.

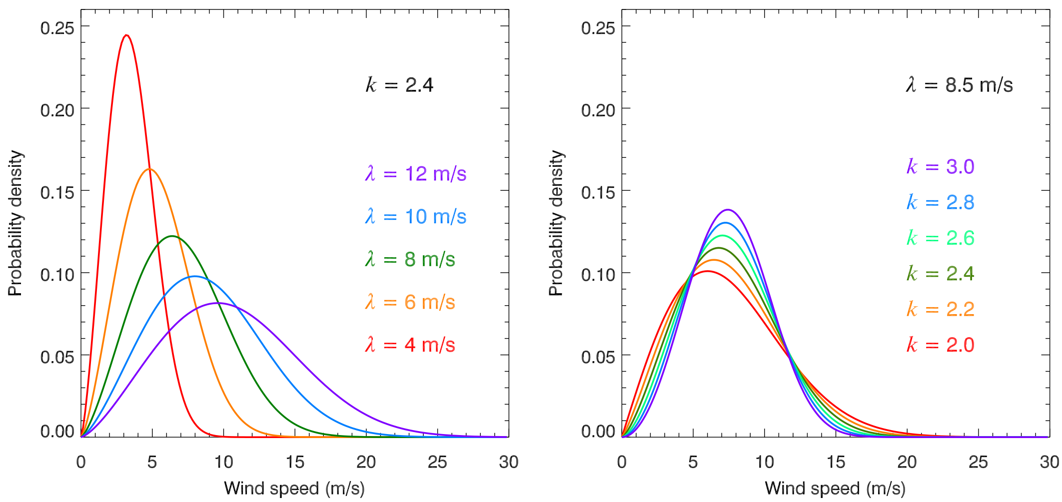

Figure 4. Demonstrations of Weibull distribution PDFs when varying the scale parameter (λ, left) and the shape parameter (k, right). Values chosen for display reflect those seen in our results.

Here we can see the differences in the spreads of the different decades: nine of the ten years of the 1990s (i.e. of the years 1990–1999 inclusive) are in the top half of the distribution, but only a couple are in the top 10. The 1980s includes some very high and very low wind years. The 2000s are also well-spread (6 yr in the top half, 4 yr in the bottom half; note 2008 is in the top 10), but it is 2010 that is the extreme low-wind year. This is because, since we are using calendar years, 2010 is hit by the low winds (or lack of high winds) associated with the extreme cold temperatures in January–February and November–December that year (e.g. Prior and Kendon, 2011b,a).

3 Summary and conclusions

Using the Twentieth Century Reanalysis, we have analysed the distribution of wind speeds over Europe, and how it has varied over 140 yr of daily data. The regions with the highest long-term average wind speeds, and highest day-to-day variabilities, are in the north-east Atlantic, and the data exhibits a strong land–sea contrast. Most areas show no clear trends over time in the mean wind speed or its variability; even in those areas where a trend is statistically significant, the magnitude is so small that it is still questionable whether it is physically meaningful or in any way relevant for applications such as wind energy. Long-term trends are difficult to distinguish from natural variability, and the variability is much greater than the uncertainties in the data.

However, the decadal-scale variations in the long time series help us understand the behaviour of recent decades in a long-term context. For the region that we have illustrated as an example (covering eastern England), we can see that the variations seen in wind speeds in the past 20–30 yr are typical of the natural variability of this region. Indeed, the past thirty years do not cover the full range of variability seen in the 140-yr time series, e.g. not capturing the the lower-wind episodes of the 1970s and 1900s in England. Note that, while the results do not depend qualitatively on the precise area in question, there is significant country-scale variability across Europe, both quantitatively and qualitatively.

Overall, we have shown that long-term data sets are essential in understanding wind speed distributions across Europe. In subsequent papers, we will describe our analysis and results in more detail, including a comparison with other data sets.

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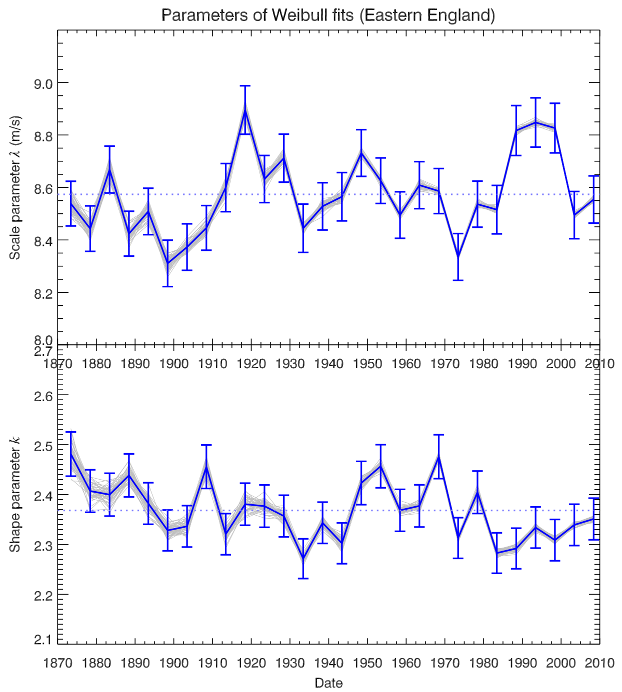

Figure 5. Time series (in 5-yr bins) of the Weibull scale and shape parameters for our sample region covering eastern England. The individual ensemble members are shown as grey lines (note that since ensemble members are discontinuous in these 5-yr steps, the lines do not reflect actual time series, but are plotted merely to guide the eye). The blue line shows the ensemble-means of the Weibull parameters in each step, with the error bars given by the ensemble-means of the estimated standard errors from the fits. The long-term means of the ensemble-mean time series are plotted as dotted lines.

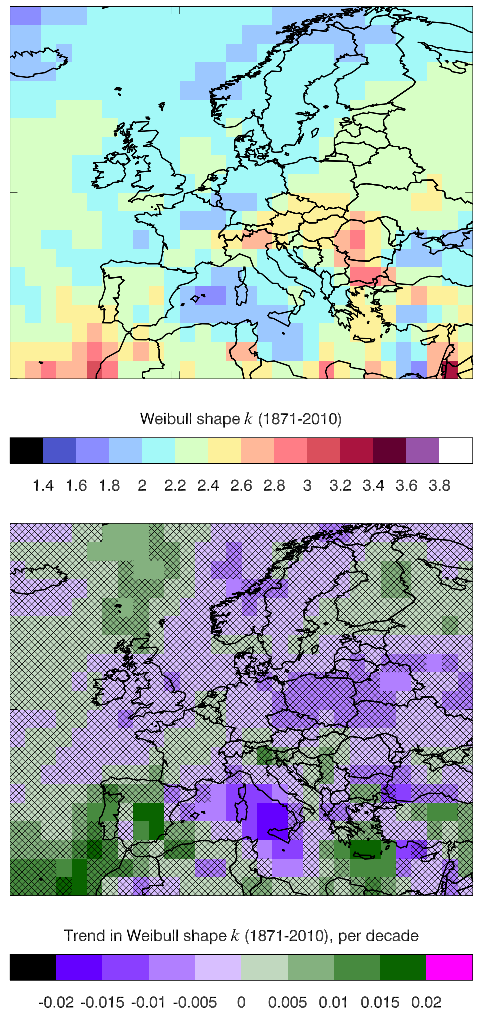

Figure 6. Maps of the long-term mean of the ensemble-mean time series of Weibull shape parameters (top), and the trend from linear regression on those time series (bottom). As before, areas where the trend is not significantly different from zero are shaded.

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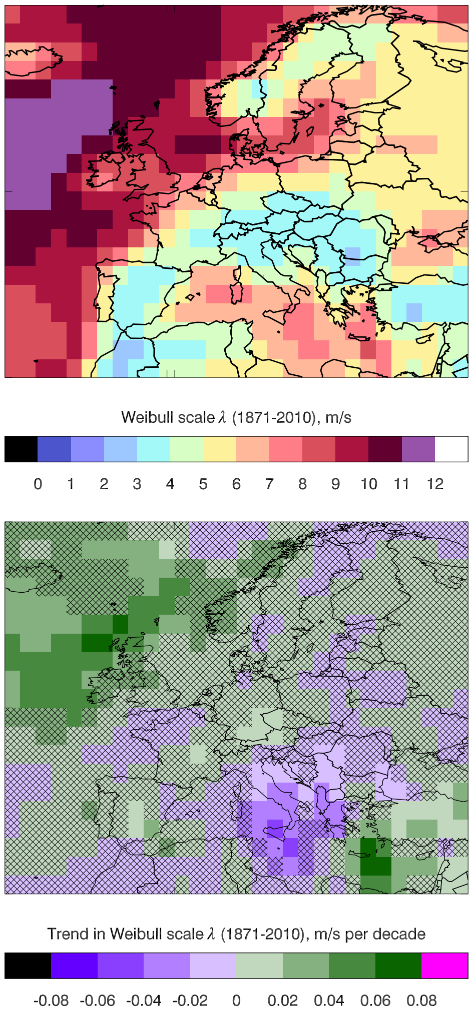

Figure 7. As Fig. 6, but for the Weibull scale parameters.

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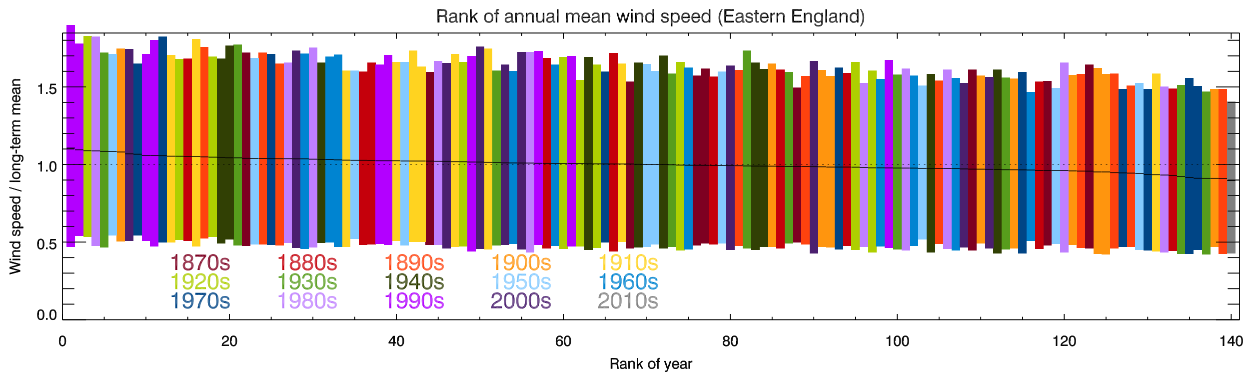

Figure 8. Annual mean wind speeds (black line) in the eastern England region, divided by the 140-yr mean, and plotted in rank order. The vertical bars (one for each year, coloured by decade) show the 10th and 90th percentile of the daily winds each year.

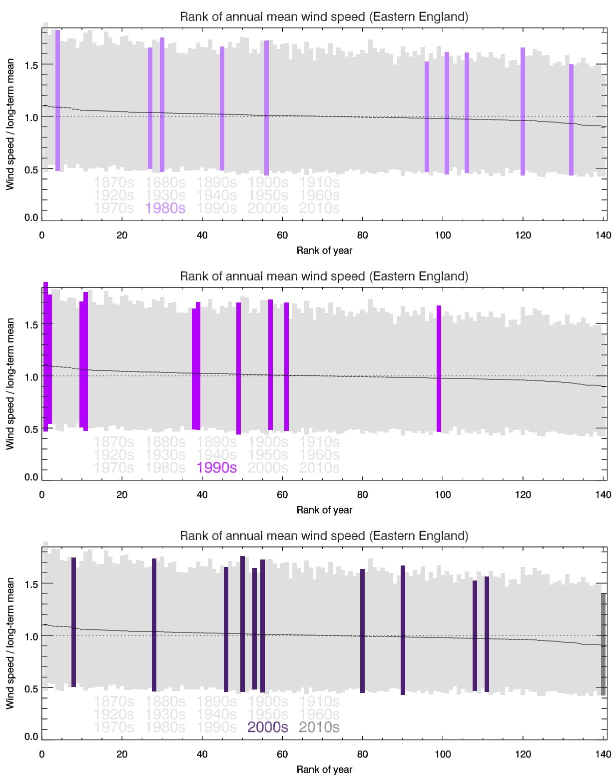

Figure 9. As Fig. 8, but highlighting the past three decades separately. We have included 2010 as an additional year in the 2000s' plot.